Influence of Combined Tension and Torsion on the Performance of REBCO Superconducting Tapes

Ashok KB, Rijo Jacob Thomas, Jose Prakash Mathai, and Arend Nijhuis

***Abstract*—Rare-earth-barium-copper-oxide (REBCO) coated conductor tapes are promising materials for superconducting cables and wires. Simulation studies of the impact of the mechanical loading on the degradation of superconducting tapes give a better understanding on the role of different geometrical parameters like tape width and thicknesses of constituent layers. In this article, a detailed analysis of combined tensile and torsional loading on REBCO tape is carried out. The results show that the thickness of each constituting layer of the tape influences the ability of the tape to withstand tensile and torsional loads. Although increasing the width of the tape increases the maximum allowable tensile load, it decreases its ability to withstand the torsional load. The angle of twist is increased from 0.18 to 0.72 °/mm, and the maximum applied tensile strain that can be applied is decreased from 0.65% to 0.3%. The maximum allowable angle of twist is decreased from 4 to 0.93 °/mm with the increase in the tape width from 3 to 12 mm under pure torsion. The critical current retention capacity of the tape changes with different geometric parameters of the tape. The findings are useful in determining appropriate values for the thicknesses of each layer and width of the tape corresponding to the magnitude of pure tensile, pure torsional and combined tensile and torsional loads experienced.**

***Index Terms*—Finite element analysis, intrinsic axial strain, rare-earth-barium-copper-oxide (REBCO) tape, torsional load, tensile load.**

I. Introduction

RARE-EARTH-BARIUM-COPPER-OXIDE (REBCO) tapes can carry large current at liquid nitrogen temperatures. However, since these materials are brittle, they are sensitive to mechanical loads. Forces like tension, torsion, and bending influence the strain in the REBCO tapes and thereby its current carrying capacity. For strain levels beyond the irreversibility limit of the superconducting REBCO layer, permanent degradation occurs. This had been reported for bismuth strontium calcium copper oxide (Bi2223) [1], [2] and REBCO conductors [3], [4], [5], [6]. The influence of intrinsic axial strain on critical current degradation on REBCO tape demonstrates that the characteristics of the substrate, and the thicknesses of constituting layers are crucial [4], [7]. The irreversibility limit of the tape depends largely on these parameters, and therefore the effect of these parameters needs to be analyzed in detail. Ilin et al. [8] proposed the irreversibility limit as 0.45% intrinsic axial strain as the criterion for the degradation of the tape. This criterion is applicable to both tensile and torsional load cases [8].

The influence of different mechanical loads during the winding of HTS tape on its degradation, revealed that torsional strain is less significant than bending and tensile loading [2], [9]. The width of the tape is reported to be the most crucial parameter under torsional loading, because the longitudinal strain state of the tape along the width changes with torsion [6]. The thickness of the tape also affects the tape degradation. A tape with smaller thickness shows less degradation compared to the thicker one under torsion [2]. It is reported that the torsional strain also helps to increase critical current slightly in the initial stage. However, with a further increase in torsion, the critical current density decreases sharply (below the critical twist pitch limit) [8].

Allen et al. [10] performed numerical simulations under different tensile and torsional loads on REBCO tape for a specific geometry condition, and found that gradual and sharp critical current degradation occurred below 100 mm twist pitch. The 5% critical current degradation for BSCCO tape and yttrium barium cupric oxide (YBCO) tape is reported in another literature, when the twist pitch reached below 114 mm and 90 mm, respectively [11]. Shin et al. [12] reported that YBCO tape of 4.3 mm wide and 60 mm long can withstand a 270º angle of twist with 5% critical current degradation. However, for 95% critical current retention, 4.19 wide SmBCO tape can withstand 240º of angle of twist [13]. In total, 5% critical current degradation occurred for 4 mm wide REBCO tape manufactured by different manufacturing techniques such as reactive coevaporation by deposition and reaction and metal-organic chemical vapour deposition at 300º and 255º angle of twist, respectively [14]. Though the modeling of REBCO tapes subjected to different mechanical loading conditions such as thermal loading, tension, bending, and torsion has been reported by various researchers [8], [10], [15], [16], detailed modeling of REBCO tape subjected to both tensile and torsional loading for wide changes in geometrical parameters such as Hastelloy thickness, copper thickness, and

Manuscript received 16 June 2022; revised 2 January 2023; accepted 8 January 2023. Date of publication 11 January 2023; date of current version 30 January 2023. This work was supported in part by the TKM College of Engineering, Kollam, Kerala, India and in part by the EMS Group, University of Twente, The Netherlands. This article was recommended by Associate Editor V. Selvamanickam. *(Corresponding author: Ashok KB.)*

Ashok KB and Rijo Jacob Thomas are with the Department of Mechanical Engineering, TKM College of Engineering, Kollam 691005, India, and also with the APJ Abdul Kalam Technological University, Thiruvananthapuram 695016, India (e-mail: ashokkb189@gmail.com; rijojthomas@gmail.com).

Jose Prakash Mathai is with the TKM Institute of Technology, Kollam 691505, India, and also with the APJ Abdul Kalam Technological University, Thiruvananthapuram 695016, India (e-mail: jpmmech@yahoo.co.in).

Arend Nijhuis is with the Faculty of Science and Technology, University of Twente, 7522NB Enschede, The Netherlands. (e-mail: a.nijhuis@utwente.nl).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2023.3236010.

Digital Object Identifier 10.1109/TASC.2023.3236010

1051-8223 © 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See https://www.ieee.org/publications/rights/index.html for more information.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

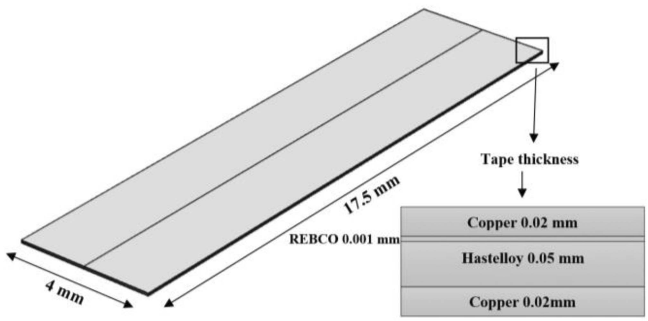

Fig. 1. Schematic showing the geometry and dimensions of the section modeled and the constituting layers of the REBCO tape.

tape width is scarce in the open literature. Even though it is reported that the thickness of copper and REBCO layers also depends on residual compressive strain induced in the REBCO layer [17], there are limited studies that have analyzed the effect of residual strain on the tape performance under torsional and tensile loads.

This article presents a detailed finite element (FE) simulation of the three-dimensional stress-strain state in REBCO tape under pure and combined tensile and torsional loads. The article has considered the temperature-dependent elastic-plastic properties of the tape components. The simulation is performed starting with the tape processing conditions during its manufacturing up to cooling down of the tape to liquid nitrogen temperature thus including the effect of residual strain on the tape performance. Parametric studies have been performed to understand the effect of variation in thickness and width of various constituting layers of the tape on the performance of superconducting REBCO tape subjected to tensile loading, torsional loading, and combined tensile and torsional loading.

II. Modeling

The modeling of the REBCO tape with its multiple layers is carried out using COMSOL Multiphysics software. For modeling the layers, a brick element with 27 nodes is selected and used throughout, as it is recommended by COMSOL Multiphysics developers for a geometry having thin layers. A REBCO tape of 70 mm length is taken for consideration. In order to reduce the computational effort, only a symmetrical part of the tape is modeled.

A schematic showing the geometry and the dimensions of the section of REBCO tape modeled, including the layers of the tape, is shown in Fig. 1. The tape has the dimension of 17.5 × 4 × 0.091 mm (length × width × thickness) with its constituting layers of copper, Hastelloy and REBCO. The selected mesh size is 72 elements along the length, 24 elements along the width, and 4 elements along the thickness. Material properties used in this article is provided in Table I. In order to understand the effect of varying the tape width, it is varied from 3 to 12 mm. Similarly, the thickness of Hastelloy layer is varied from 0.02 to 0.05 mm, and the copper thickness is varied from 0.005 to 0.04 mm. In all the tensile and torsional load cases, the intrinsic axial strain developed in the REBCO layer is calculated. If the induced axial strain exceeds the irreversible limit, the tape is considered degraded.

TABLE I
Properties of the Layer Materials of the Superconductor [8]

	Young's modulus (GPa)	*Yield stress (MPa)*	*Poisson's ratio*	*Thermal expansion coefficient(K^{-1})*
Hastelloy (RT)	*223*	*891*	*0.307*	*1.34×10^{-5}*
Hastelloy (77 K)	*228*	*1141*	*0.307*	*1.34×10^{-5}*
Copper (RT)	*80*	*120*	*0.34*	*1.77×10^{-5}*
Copper (77 K)	*98*	*146*	*0.34*	*1.77×10^{-5}*
REBCO	*157*	*--*	*0.3*	*1.1×10^{-5}*

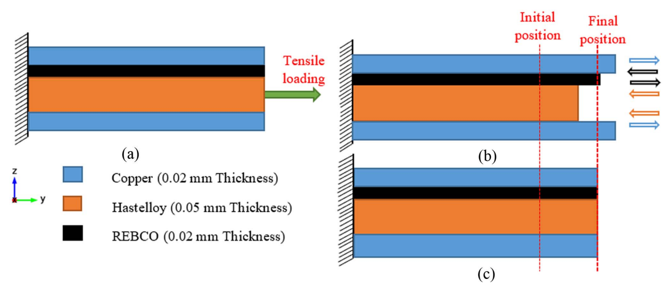

Fig. 2. Pictorial representation of the effect of different dissimilar material layers on the induced strain in the REBCO tape; (a) before loading; (b) under loading with no interfacial bonding between the layers; (c) under loading with interfacial bonding between the layers.

Different material layers constitute the REBCO tape, and each layer has its own significance and material properties [8], [18]. The bonding between the layers also will have an impact on the eventual force transmitted among the layers. In addition to this, the thermal stress-induced residual strain from the production process of the REBCO tape, also will have an influence on the strain-induced [16]. In the case of the properties of dissimilar material layers, the effect is mutually coupled. For instance, when the applied stress is the same, Hastelloy with a high Young's modulus value will have a lesser strain than copper and REBCO. It may be noted that Young's modulus values of Hastelloy, REBCO and copper are 225, 157, and 80 GPa, respectively. Since copper has a lower value of Young's modulus, it undergoes more tensile strain when the tensile force is applied on the REBCO tape. This is depicted in Fig. 2 using a representative diagram. The lower Young's moduli of REBCO and Hastelloy will resist the pulling of the copper layer, see the small arrow marks in the right part of Fig. 2.

Another important parameter that may affect the intrinsic axial strain induced upon tensile loading would be the dimensions of individual layers that include thickness, length, and width. When changing either the length or width of the tape, the volume fraction of each layer remains the same. In the case of pure torsional and combined tensile and torsional loading, the effects of properties of dissimilar material layers, bonding between layers, and the residual strain will eventually influence the intrinsic axial strain induced in the REBCO layer. However, the mechanism of action and the failure will be different from that of the pure tensile case.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

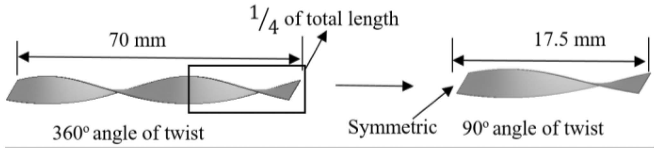

Fig. 3. Pictorial representation showing the tape symmetry and the section of the tape modeled.

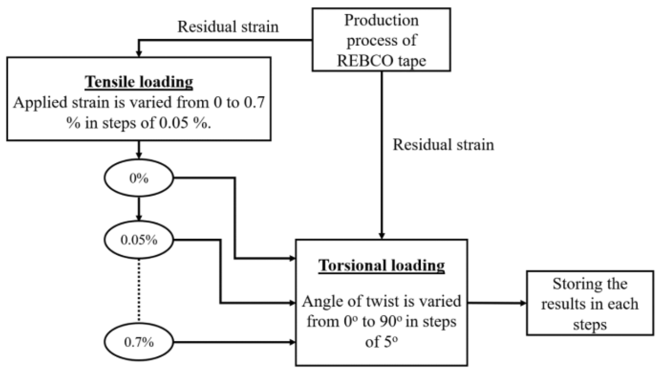

Fig. 4. Methodology adopted for providing pure torsional, pure tensile, and combined tensile and torsional loads on REBCO tape in FE modeling.

Modeling can be divided into three separate stages. First, the process of metal-organic chemical vapour deposition at 1020 K that coats the REBCO film on the substrate. Second, for electrical and thermal stability, copper is electroplated at 333 K above and below the tape. Finally, the entire composite is cooled down to cryogenic (liquid nitrogen) temperature, where the mechanical load is applied. This electroplating of copper is done by a method called "birth and death method" [19]. The passive copper layer is permitted to bend freely during the initial cool-down without contributing any stress. This is achieved by providing a very low value of young's modulus to the copper. Subsequently, Copper, REBCO, and Hastelloy were cooled down from 333 K to 77 K by giving the actual value of the young's modulus to copper.

For providing the torsional load, the angle of twist is decided to be varied from 0º to 360º. When providing the full torsional load with an angle of twist of 360° for the entire 70 mm tape, an equivalent load is experienced in 1/4; of the tape length (17.5 mm) with 90º of the angle of twist in the symmetrical part. A symmetrical boundary condition is provided at one end of the section of the tape modeled. The pictorial representation of the tape symmetry and the section of the tape modeled is shown in Fig. 3.

For providing pure torsion, pure tension, and combined tension and torsional loads, the procedure followed is given in Fig. 4. Initially, the production process is modeled to determine the amount of residual strain developed in the tape. In the second stage, the tensile load is varied from 0 to 0.7% of the original dimension in 15 steps with an increment of 0.05%. In the third stage for each tensile load, the torsional load is varied by changing the angle of twist from 0º to 90º about the y-axis with a step size 18, as it is depicted in Fig. 4. The pure tensile, pure torsional, and the combined torsion and tension cases are obtained and stored.

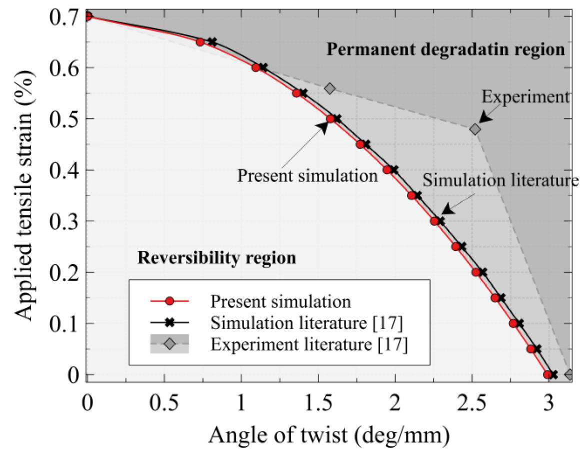

Fig. 5. Comparison of the simulation results of the this article with experimental and simulation data available in the literature [8].

III. Validation

The results obtained through the developed FE model are compared with the experimental and simulation work reported in the literature [8]. The comparison obtained is plotted as a graph in Fig. 5. Fig. 5 demarcates the reversible and irreversible regions based on the critical strain limit of 0.45% in the REBCO layer under the combined loading of tension and torsion.

Comparison between the experimental data available in the literature and the present simulation results show reasonably good agreement (6% average difference) except in one experimental point. The difference between the simulation and the experimental results may be due to the sensitivity difference in detecting irreversibility for tensile and torsional loads. Ilin et al. [8] mentioned that the sensitivity is sufficiently high for pure tensile strain but very small for torsional strain at a critical current-criterion of 10 μVm^{-1}. Fig. 5 shows that there is close agreement between the simulation study reported in the literature and the present study (1.2% difference). The FE model developed is found to be good enough to be used for performing the planned studies. The parameters varied involve thickness of the copper layer, the thickness of the Hastelloy layer and the width of the tape. Both the individual effects of tensile and torsional loads as well as their combined effects are investigated in the parametric studies. The results obtained under pure tensile, pure torsional, and combined tensile and torsional loadings under different geometric and operating conditions are presented.

IV. Result and Discussion

In this section, the results of pure tensile loading are presented first and then, the results of the combined tensile and torsional loading are provided. The critical force marking degradation at 0.45% intrinsic axial strain in the REBCO layer, corresponding to different loading conditions, is determined for various sizes of tape.

A. *Tensile Axial Loading*

The effects of pure tensile loading on the degradation of the tape and the changes obtained with variations in the geometric parameters of the tape are presented.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

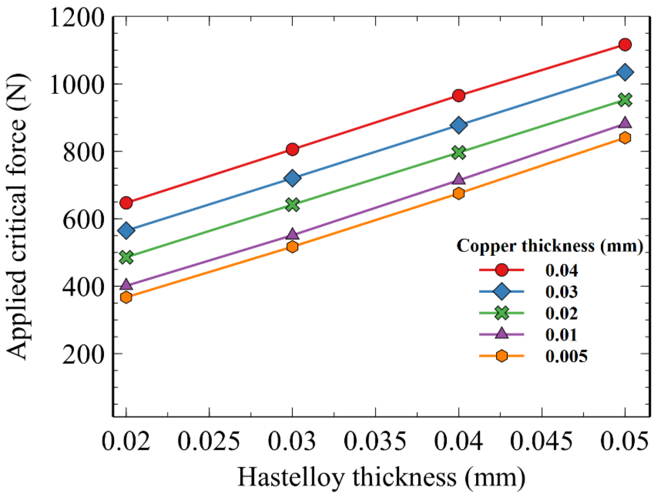

Fig. 6. Effect of Hastelloy and copper thickness on the applied critical force.

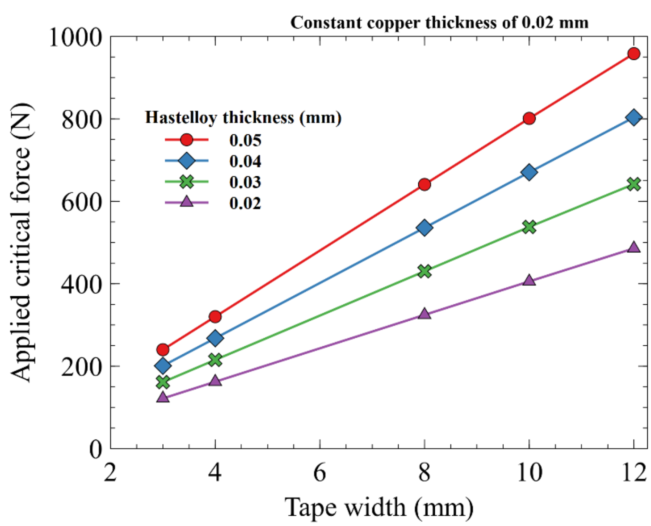

Fig. 7. Effect of tape width on the applied critical force.

1) Variations in Thicknesses and Width: The changes in the applied critical force with changes in geometrical parameters like the thickness of Hastelloy and copper layers are represented in Fig. 6.

As expected, the increase in the thicknesses of Hastelloy and copper layers results in a practical linear increase of the applied critical force. And because of the respective material properties, increasing the thickness of the Hastelloy layer has more influence as compared to increasing the thickness of the copper layers. For the case of the thickest copper layer (0.04 mm), when the Hastelloy thickness is increased from 0.02 to 0.05 mm (150% increase), the applied critical force is increased by 73%. When the copper thickness is increased from 0.005 to 0.04 mm (700% increase), the applied critical force is increased by only 33%. This is for the case of the thinnest Hastelloy layer (0.02 mm).

The effect of tape width on the applied critical force is depicted in Fig. 7. Increasing the Hastelloy thickness from 0.02 to 0.05 mm (150% increase), increases the applied critical force by 97% for all the tape widths.

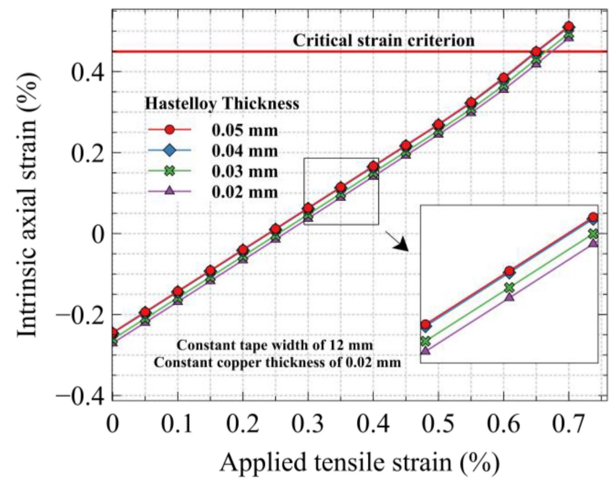

Fig. 8. Effect of Hastelloy thickness on intrinsic axial strain under pure tensile loading.

2) Variation in Hastelloy Thickness: The effect of pure tensile loading on intrinsic axial strain on the REBCO tape for different Hastelloy thicknesses is shown in Fig. 8.

As expected for any given thickness of Hastelloy, with an increase in applied tensile strain, there is a directly proportional increase in the intrinsic axial strain in the REBCO layer. It may be noted that for the initial values of applied tensile strain, the induced intrinsic axial strain values are negative, which indicates that the strain is compressive. This is due to the presence of the residual strain developed in the REBCO tape during its production stage. It is for the same reason that there is some compressive strain even when the applied tensile strain is zero. It may be noted that at zero applied strain, the residual strain in the REBCO layer is −0.244% (at 0.05 mm Hastelloy thickness). When the Hastelloy thickness is reduced to 0.02 mm, the residual strain increases from −0.244% to −0.27%, which is about 2.7%. Beyond 0.25% of the applied tensile strain, the strain in the REBCO layer is changed from compressive to tensile (negative to positive values).

The graph also depicts that when decreasing the thickness of the Hastelloy, the intrinsic axial strain in the REBCO layer is decreased is due to the changes in the percentage of volume fraction and the bonding between different layers with variation in thickness of Hastelloy (see Fig. 2). Irrespective of the thickness of Hastelloy, at high values of applied tensile strain, the tape is degraded (marked as the horizontal solid line at the top of the graph). Therefore, while using the tape, measures need to be taken to ensure that the magnitude of the applied tensile strain is not more than these irreversible limits.

It may be observed that when decreasing the thickness of Hastelloy there is a slight increase in the critical strain value. However, it may be noted that the applied critical force also decreased with decreasing the Hastelloy thickness as observed in Fig. 6. The applied tensile strain is increased by 3.75% as the thickness of Hastelloy decreased from 0.05 to 0.02 mm (60% decrease). It may be noted that in all the cases, the thickness of the copper layer is kept constant at 0.02 mm, and the tape width is 12 mm.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

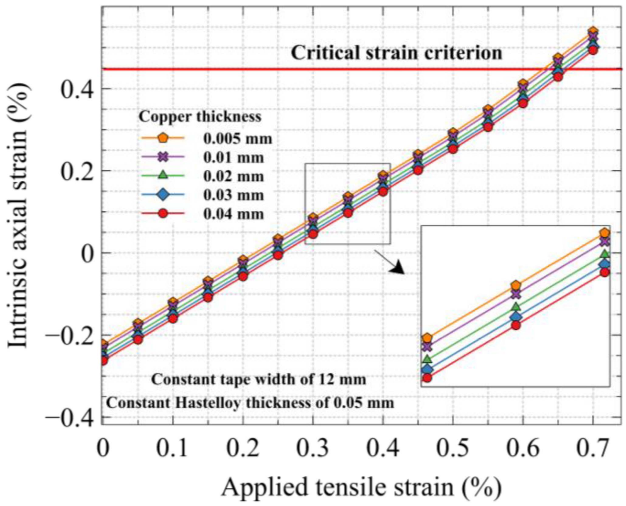

Fig. 9. Effect of copper thickness on intrinsic axial strain under pure tensile load.

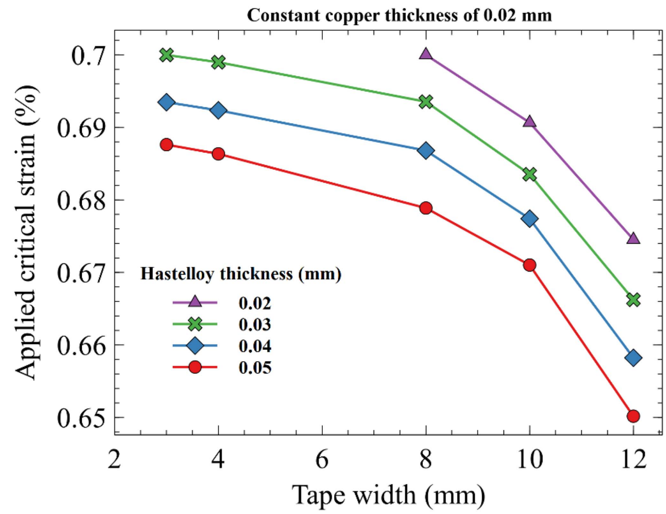

Fig. 10. Variation in critical applied strain with changes in tape width for different Hastelloy thickness under pure tensile loading.

3) Variation in the Induced Strain in REBCO With Change in Copper Thickness: Fig. 9 depicts the effect of varying copper thickness on intrinsic axial strain in the REBCO layer under pure tensile load. It is found that the variation in the copper thickness affects the intrinsic axial strain induced in the REBCO layer. However, in contrast to the case Hastelloy thickness, the induced intrinsic axial strain value increases with an increase in the copper thickness. It may be observed that when the copper thickness is increased from 0.005 to 0.04 mm, the difference in the intrinsic axial strain is increased by 4%. The critical strain value increases by 5.3% as the copper thickness increases from 0.005 to 0.04 mm. It may be due to the changes in the percentage of volume fraction and the bonding between different layers with variations in the thickness of copper thickness (see Fig. 2).

The residual strain values are also increased with an increase in copper thickness. For the maximum variation of the copper thickness (0.005 mm to 0.04 mm), the residual strain is increased from −0.223 to −0.262%. Note that the thickness of Hastelloy kept constant at 0.05 mm and tape width at 12 mm. At high values of applied tensile strain, the tape is degraded (marked as the horizontal solid line at the top of the graph). However, as the copper thickness increases, the applied tensile strain that can be endured without causing degradation also increases.

4) Variation in the Induced Strain in REBCO With Change in Tape Width: The variation in the critical applied tensile strain with changes in the tape width corresponding to different thicknesses of Hastelloy and copper layers is investigated and the results are presented in Figs. 10 and 11.

Fig. 10 depicts that changes in critical applied tensile strain with tape width for different Hastelloy thicknesses. With the increase in tape width, though the trend remains the same for all widths, there is a reduction in the value of the critical applied tensile strain. With higher values of tape width, the degradation is faster (lower values for critical applied tensile strain). But it may be noted that, the larger tapes able to withstand more force without any degradation as it is evident from Fig. 7. With the increase in thickness of the Hastelloy layer, the amount of

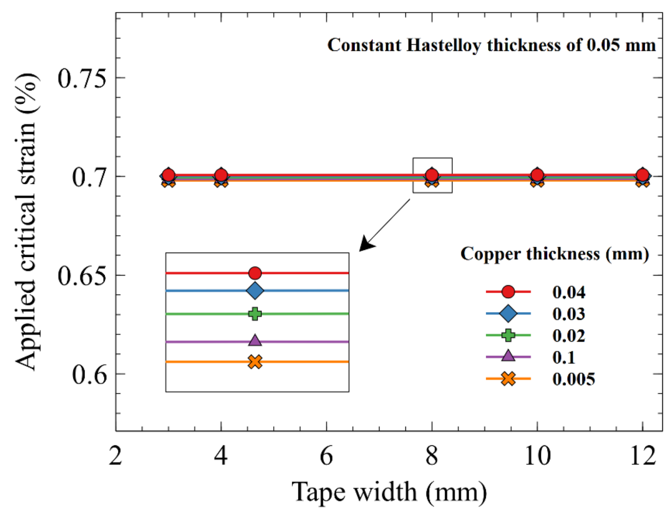

Fig. 11. Variation in critical applied tensile strain with changes in tape width for different copper thicknesses under pure tensile loading.

material available to withstand the force applied also increases. Therefore, the critical strain value reduces. At 12 mm tape, when the Hastelloy thickness is increased from 0.02 to 0.05 mm, the critical applied tensile strain values are decreased by about 36%.

The variation in critical applied tensile strain with changes in the tape width is depicted in Fig. 11. It can be observed that the tape width does not have any significant influence. Also, with the change in copper thickness, there is no prominent effect. For instance, with an increase in thickness of copper from 0.005 to 0.04 mm (about 700%), the critical applied tensile strain value is increased only by 3.9%.

B. Influence of Combined Tension and Torsion on the Performance of the REBCO Tape

Degradation of REBCO tape under the combined load of tension and torsion is relevant since the tapes are generally subjected to such a combination of forces during the winding

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

of tapes to produce superconducting cables, especially in cases of CORC and twisted stack type of tape configurations. If the intrinsic axial strain developed in the REBCO layer under such combined forces are within the critical limit, then the tape can be considered safe. Therefore, during the production process of superconducting cables, care is to be taken such that the combined tensile load and torsional loads are within these critical limits for any given dimensions of the REBCO tape. Otherwise, if the critical limits are crossed, then the tape is degraded, losing its superconducting behavior. The cable will become useless and needs to be discarded.

The critical degradation points corresponding to the combined tension and torsion loads are determined for various sizes of the tape. The effects of change in the geometrical parameters such as the thickness of Hastelloy and copper layers, the width of the tape are also analyzed under this combined loading. The changes in the degradation limits with variation in thickness of Hastelloy and copper layers and the width of the tape is plotted in the subsequent sections.

1) Effect of Combined Tensile and Torsional Loading on REBCO With Changes in Hastelloy Thickness: The degradation limits of REBCO tape under a combination of tensile and torsional loads is given in Fig. 12. The curves in the graphs show the critical limits, and the area above that is the degradation region (denoted by the shaded region). The graph shows that when the angle of twist is high then, the tensile load that can be applied will be less. For instance, if the angle of twist is 0.18 °/mm, then the maximum value of applied tensile strain is 0.65%. When the angle of twist is increased from 0.18 to 0.72 °/mm (300% increase), the maximum value of applied tensile strain is decreased to 0.3% (about 54% decrease). When the angle of twist is zero, the applied tensile strain can be a maximum of about 0.7% (pure tension case). Similarly, when the applied tensile strain is zero, the maximum angle of twist that can be provided is 0.93 °/mm (pure torsion case).

Fig. 12 also depicts that increasing the thickness of the Hastelloy layer has a less significant effect on the critical limits. When the Hastelloy thickness is reduced from 0.05 to 0.02 mm (about 60% decrease), the angle of twist can be increased by only 2.2% for the pure torsion case. The width of the tape is kept constant at 12 mm in the case of Fig. 12(a). The effect of reducing the tape width to 10 mm is depicted in Fig. 12(b). Comparing Fig. 12(a) and (b) reveals that a 12 mm width tape degrade faster than a 10 mm one. It is also observed that 10 mm width tape can withstand 1.2 °/mm of the angle of twist for the pure torsion case. This is about 28% more than that of the 12 mm case.

2) Effect of Combined Tensile and Torsional Loading on REBCO With Change in Copper Thickness: The effect of copper thickness on the degradation of the REBCO tape under combined tension and torsional loading is presented as Fig. 13. The maximum angle of twist that can be applied is 0.92 °/mm when the tensile load is zero (pure torsion). On the other hand, the maximum applied tensile strain that can be applied is 0.65% when the torsional load is zero (pure tension). This is for the case where the copper thickness is the minimum (0.005 mm). The effect of increasing the thickness of copper layers though has a positive increase in degradation limit, the influences is not very substantial.

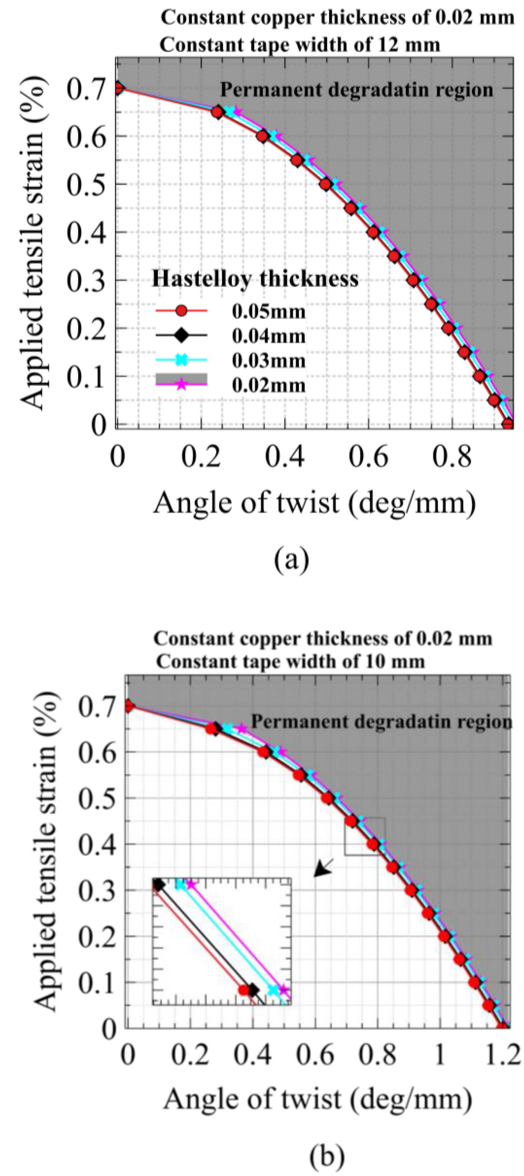

Fig. 12. (a) Dependence of critical strain in the REBCO layer under the combined loading of tension and torsion at different Hastelloy thickness for 12 mm tape width. (b) Dependence of critical strain in the REBCO layer under the combined loading of tension and torsion at different Hastelloy thickness for 10 mm tape width.

It is found that the smaller copper thickness tape degrades faster. For the maximum copper thickness (0.04 mm), under pure torsion, the angle of twist that can be applied increases to 0.95 °/mm (about 3.2%). Whereas, for the same copper thickness, under pure tension, the applied tensile strain increases to 0.7%, which is about 7.7%.

3) Effect of Combined Tensile and Torsional Loading on the REBCO With Changes in the Tape Width: The effect of decreasing the width of the tape on the degradation under combined tension and torsional loading is presented in Fig. 14.

With the decrease in width of the tape, the critical limits are pushed further, giving more flexibility for the manufacturers in terms of combined tensile and torsional loads. For instance, decreasing the tape width from 12 to 3 mm (75% decrease), has increased the maximum allowable angle of twist from 0.93

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

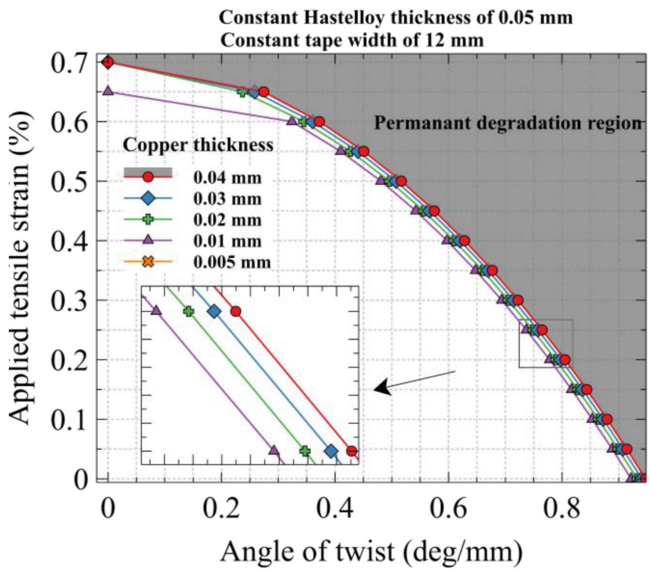

Fig. 13. Effect of copper thickness on critical strain under combined tension and torsion.

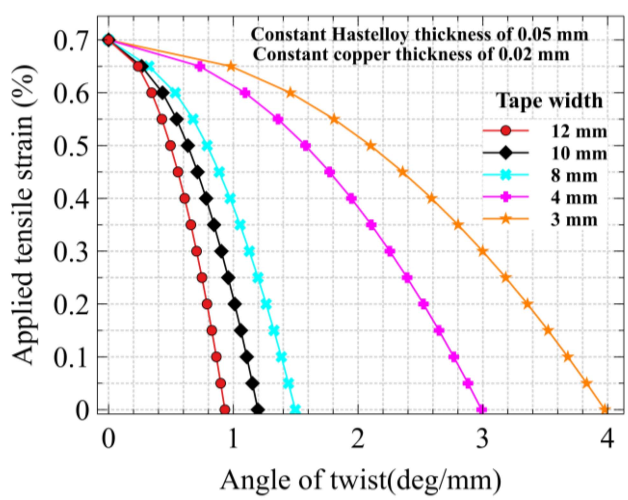

Fig. 14. Effect of tape width on critical strain under combined tension and torsion.

to 4 °/mm (326% increase) for the pure torsional case. However, in the pure tension case, there is no much effect in the change in tape width. Both 12 mm and 3 mm tape degrade at the same point, which is 0.7% applied tensile strain. From the pure tensile case with an increase in the angle of twist, the influence of tape width becomes prominent. This is due to the fact that in the pure tensile loading, changing the width of the tape will not have much effect on the induced axial strain. With the increase in the tape width, the cross-sectional area is proportionally increased. Whereas with torsional loading, the failure will be happening at the edges, and smaller tape width produces lesser strain in the tape. Therefore, the width of the tape has a very significant influence on the combined tensile and torsional loading as well as the pure torsional loading. If the width of the tape is high, under combined tensile and torsional loading, the tape will fail quickly with an increase in the angle of twist. This is evident from Fig. 14 as the slope becomes steeper with the increase in the tape width.

C. Electrical Performance of REBCO Tape Under Combined Tension and Torsion

Superconducting tapes after being converted to cables/ wires, find application in various systems, including magnets where a large amount of current needs to be passed through them. Since the tape being superconducting (zero electrical resistance), such high currents can be transmitted. However, induced strain due to mechanical forces on them can degrade the superconducting tape producing some electrical resistance in it. Though the value of such resistance produced will be small, owing to the high value of current passing through it, results in situations like quenching and can permanently damage the cable/ wire. Each superconducting tape has a maximum capacity for carrying current, and this critical current will reduce with the degradation of the tape. In other words, the amount of degradation of any superconducting tape can be identified in terms of its current carrying capacity. This is termed as the electrical performance of superconductors, and it is affected due to changes in mechanical forces on the tape, including tension, torsion, and combined tension and torsion. In this section, the effect of the mechanical forces on the induced strain and its corresponding amount of degradation of the superconducting tape in terms of changes in the critical current is investigated.

The critical current depends upon the intrinsic axial strain. The intrinsic axial strain is not constant across the width of the tape in pure torsion and combined tension and torsional cases. From moving from the center line to the edges of the tape along the width (x-direction), the strain-induced will be more under torsion. Correspondingly, the current-carrying capacity also will be varying depending upon the strain-induced. Therefore, the overall current carrying capacity of the tape has to be determined using [20]

$$\text{Ic} = t_s \int_{-\frac{w}{2}}^{\frac{w}{2}} j_c\ (\varepsilon_x)\, dx \tag{1}$$

where the critical current "I_c" of a twisted tape is written as a summation of critical current densities "$j_c(\varepsilon_x)$" over the tape cross section of the width "w" and the thickness "t_s". This expression shows that the critical current density is a function of the intrinsic axial strain. A more accurate empirical expression (2) is provided in the literature [20], and it is developed using the data published by SuperPower on YBCO [21]

$$\begin{aligned}\frac{I_c}{I_{co}} &= 0.057713\text{x}10^{12}\varepsilon_\text{x}^6 \\ &\quad - 0.03979215\text{x}10^{10}\varepsilon_\text{x}^5 - .02090279\text{x}10^8 \\ &\varepsilon_\text{x}^4 + 0.02385557\text{x}10^6\varepsilon_\text{x}^3 \\ &\quad - 0.1668065\text{x}10^4\varepsilon_\text{x}^2 - 0.003662115\text{x}10^2\varepsilon_\text{x} + 1\end{aligned} \tag{2}$$

where I_{co} is the critical current density at zero intrinsic axial strain. Critical current retention at particular strain is the ratio of critical current at that strain to the critical current value when the intrinsic axial strain is zero. The abovementioned expression

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

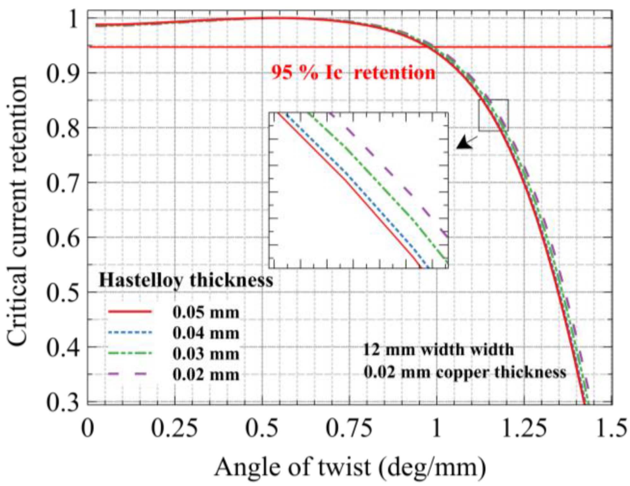

Fig. 15. Critical current retention at different Hastelloy thicknesses under pure torsion.

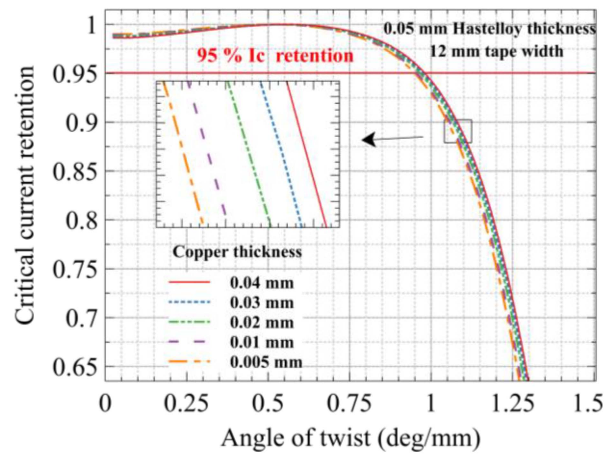

Fig. 16. Critical current retention at different copper thicknesses under pure torsion.

is used for calculating the critical current retention ($\frac{I_c}{I_{co}}$) of different cases.

D. Changes in the Critical Current Retention Under Pure Torsional Loads

1) Effect of Thickness of Hastelloy on the Critical Current Retention: The effect of thickness of the Hastelloy layer on the critical current retention under pure torsion (applied tensile strain 0% case) is depicted in Fig. 15.

The torsional load is varied by changing the angle of twist. The graph depicts that with an increase in the angle of twist, the critical current retention is good till about 0.9 °/mm, and afterwards, it has decreased considerably. For instance, a 50% increase in the angle of twist beyond 0.9 °/mm (0.9 °/mm to 1.35 °/mm) will decrease the critical current retention by about 50%. The same trend is also observed for other Hastelloy thicknesses (from 0.05 to 0.02 mm). Initially, with the increase in angle of twist, the critical current retention increases and this is due to the influence of residual strain as mentioned earlier. For this particular case, the critical current retention is 100% when the angle of twist is about 0.54 °/mm.

The graph also shows that, when decreasing the thickness of Hastelloy, the tape will able to withstand a slightly higher angle of twist without the critical current retention being affected. For instance, at 0.05 mm thickness of Hastelloy, the critical current retention of 95% is possible only up to an angle of twist of 0.96 °/mm. And when reducing the thickness of Hastelloy from 0.05 to 0.02 mm (60% decrease), the angle of twist possible (torsional load) increases to 0.99 °/mm (which is only about 2% increase). The results show the scope of reducing the thickness of Hastelloy without much effect on the electrical performance.

2) Effect of Thickness of Copper on the Critical Current Retention: The thickness of the copper layer is varied in this case instead of the Hastelloy thickness in the previous section. Changes in critical current retention under pure torsion is depicted in Fig. 16. The copper thickness is increased and also decreased from the given value (0.02 mm) to find its effects on the electrical performance.

Fig. 16 shows that, when increasing the angle of twist, the critical current retention under pure torsion is better when the thickness of copper is increased. However, when the copper thickness is decreased, the critical current retention is reduced.

At 0.04 mm thickness for the copper layer, the critical current retention of 95% is possible only up to an angle of twist of 0.98 °/mm. When the thickness of copper layers is decreased (0.005 mm), the possible angle of twist is decreased to 0.95 °/mm. The critical current retention becomes 100% when the angle of twist is about 0.54 °/mm for the given configuration. Initially, torsional load up to 0.54 °/mm, the tapes with higher values of copper thickness can retain more residual strain, and the critical current retention is less. However, torsional load beyond 0.54 °/mm the critical retention is high for tapes with higher copper thickness.

3) Effect of Tape Width on the Critical Current Retention: The effect of the width of the tape on the critical current retention under pure torsion (applied tensile strain 0% case) is depicted in Fig. 17. The width of the tape is decreased from the given value to find its effects on the electrical performance.

The results show that the width of the tape has a significant influence on critical current retention. When reducing the width of the tape from 12 to 3 mm (75% decrease), the maximum angle of twist possible without degradation increases from 0.93 to 4.1 °/mm (about 326% increase demarcated by the 95% critical current retention limit (horizontal thick line).

4) Changes in the Critical Current Retention Under Combined Tensile and Torsional Loads: Fig. 18 depicts the critical current retention of the REBCO superconducting tape under combined tensile and torsional loads. For the given range of parameters, the critical current retention varies from around 100% to 65%, as shown in the graph. From the figure, it can be understood that with a significant increase in tensile and torsional loads, the critical current retention considerably decreases.

The numerical simulation done by llin et al. [8] reported that, when the applied strain is 0.3%, then the maximum angle of twist that can withstand without any degradation is 2.29 °/mm.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

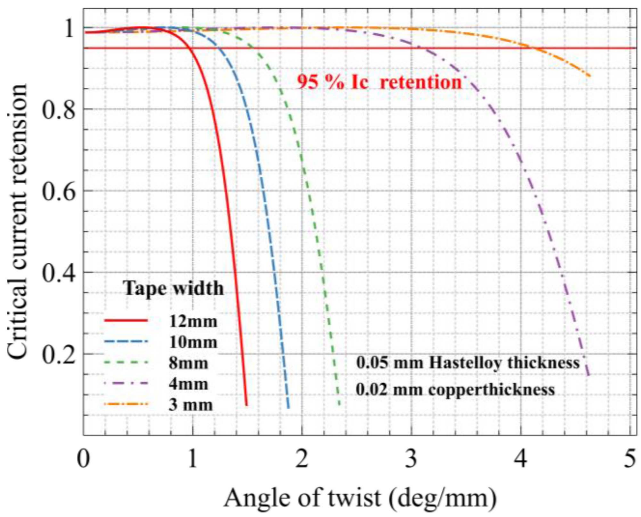

Fig. 17. Critical current retention at different tape widths, under pure torsional load.

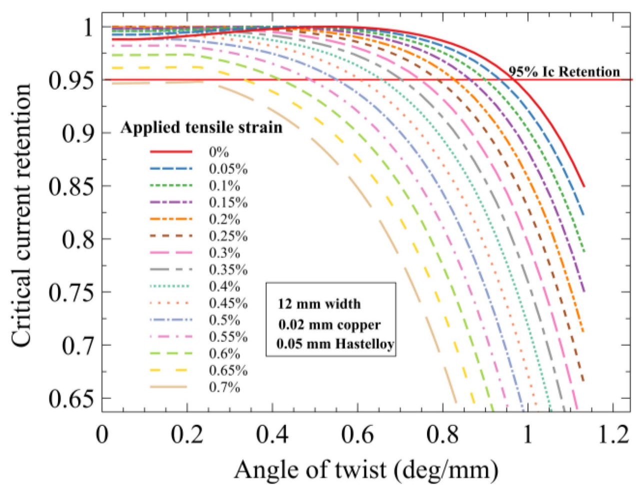

Fig. 18. Critical current retention under combined tensile and torsional load.

This article also found a similar result, the maximum allowable angle of twist without any degradation at 0.3% applied strain is 2.25 °/mm. The critical current degradation under combined tension and torsion is reported in another literature [22]. However, a direct comparison of these two studies is not possible, because this article is using 12 mm wide tape, and the literature use 4 mm wide tape. At 0.6% applied strain, 4 mm width tape can accommodate 1.8 °/mm angle of twist [22]. But in this article, 12 mm width tape at 0.6% applied strain can accommodate 0.42 °/mm. Another literature reported that 5% critical current degradation occurred for 4.01 mm GdBCO tape at 2.96 °/mm [14]. However, in this article, 5% critical current degradation is observed at 0.97 °/mm (12 mm width tape). In all the cases, a direct comparison of these 12 mm and 4 mm width tape is not possible, even though it is clear that 12 mm width tape fails first compared to 4 mm width one under pure torsion and combined tension and torsion.

It may also be noted that the critical current value first increases with an increase in the angle of twist. Once it reaches a particular strain value, then it starts decreasing for each case of applied tensile strain. Similar results were obtained for other researchers earlier [20], and it may be due to the relief of the residual strain in the tape. It may be observed that at the highest applied tensile strain (0.7% curve), even without any torsional load (0 °/mm angle of twist), the critical current retention is less than 95%. With the application of more torsional load, the entire tape is in the degraded region. On the other hand, without any tensile load (0% applied tensile strain), the maximum angle of twist that can be provided without being degraded in 0.97 °/mm. With the increase in the applied tensile strain, the rate at which the critical current retention is decreasing increases, as it is evident from the shapes of the different curves.

V. Conclusion

The influence of intrinsic axial strain induced on the degradation of REBCO tape under combined twisting and torsion has been studied. The tape parameters such as the thickness of Hastelloy and copper layers and the width of the tape are varied to evaluate the amount of degradation under pure tension, pure torsion, and combined tension and torsion loads. From the results obtained from this article, the following conclusions have arrived.

1) Under pure tensile loading, the applied tensile strain on the tape is directly proportional to intrinsic axial strain developed in the REBCO layer irrespective of any given thickness of Hastelloy and copper layers as well as for any given width of the tape. The applied tensile strain beyond which the tape degrades is found to be between 0.6% and 0.7% applied tensile strain for any thickness of layers and tape width.
2) Under combined tension and torsion, there is an inverse relationship between the applied tensile strain and the angle of twist that can be applied. When the angle of twist is increased from 0.18 to 0.72 °/mm (75% increase), the maximum value of applied tensile strain that can be applied is decreased from 0.65% to 0.3% (about 54% decrease). Decreasing the tape width further decreases the maximum value of applied tensile strain for the same increase in the angle of twist. Changing the thickness of Hastelloy and copper layers is not found to have any significant influence on the degradation of the tape.
3) It is found that under pure torsional and combined tensile and torsional load, the applied tensile strain that can be applied on the tape can be increased by decreasing the width of the tape.
4) By decreasing the tape in width, the critical limits can be pushed further giving more flexibility for the manufactures to accommodate for combined tensile and torsional loads. It is found that by decreasing the tape width from 12 to 3 mm (75% decrease), the maximum allowable angle of twist can be increased from 0.93 to 4.1 °/mm (326% increase) under pure torsional loading.
5) Under pure torsion on the other hand, decreasing the Hastelloy thickness from 0.05 to 0.02 mm (about 60%

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

decrease), will increase the maximum allowable angle of twist by only 2.2%.

6) Observation of the critical current retention under combined tension and torsion revealed that the critical current value first increases with an increase in the angle of twist. However, once it reaches a particular angle of twist (0.54 °/mm) for this case, it starts decreasing for any given applied tensile strain.
7) Changing the thickness of Hastelloy and copper layers is not found to have any significant influence on the critical current retention of the REBCO tape. When reducing the thickness of Hastelloy from 0.05 to 0.02 mm (60% decrease), the maximum allowable angle of twist is increased from 0.97 to 0.99 °/mm (2.2%). However, when the copper thickness is reduced from 0.04 to 0.005 mm (87.5% decrease), the maximum allowable angle of twist is decreased from 0.98 to 0.95 °/mm (3.1% decrease).
8) Under pure torsion, the maximum allowable angle of twist is decreased (from 4.1 to 0.97) with the increase in the tape width from 3 to 12 mm (300% increase), corresponding to 95% critical retention criteria.

The results generated are expected to help the manufactures of superconductors when developing REBCO based tapes and cables that will be subjected to tensile, torsional, combined tensile, and torsional loads.

Acknowledgment

The authors would like to thank the EMS Group, University of Twente, in carrying out the simulation work also like to thank the Department of Mechanical Engineering, TKM College of Engineering for providing the facility to carry out the work.

References

[1] H. S. Shin and K. Katagiri, "Critical current degradation behaviour in Bi-2223 superconducting tapes under bending and torsion strains," *Supercond. Sci. Technol.*, vol. 16, pp. 1012–1018, 2003, doi: 10.1088/0953-2048/16/9/309.

[2] H. S. Shin et al., "IC degradation behavior in Bi-2223 superconducting tapes under torsional deformation," *Phys. C Supercond. Appl.*, vol. 392–396, pp. 1162–1166, 2003, doi: 10.1016/S0921-4534(03)00747-0.

[3] D. C. Van Der Laan, J. D. Weiss, and D. M. McRae, "Status of CORC cables and wires for use in high-field magnets and power systems a decade after their introduction," *Supercond. Sci. Technol.*, vol. 32, 2019, Art. no. 33001, doi: 10.1088/1361-6668/aafc82.

[4] M. Sugano et al., "Tensile fracture behaviour of RE-123 coated conductors induced by discontinuous yielding in Hastelloy C-276 substrate," *Supercond. Sci. Technol.*, vol. 18, 2005, Art. no. S344, doi: 10.1088/0953-2048/18/12/020.

[5] N. Cheggour et al., "Transverse compressive stress effect in Y-Ba-Cu-O coatings on biaxially textured Ni and Ni-W substrates," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 3530–3533, Jun. 2003, doi: 10.1109/TASC.2003.812390.

[6] T. Takao et al., "Influence of bending and torsion strains on critical currents in YBCO coated conductors," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 3513–3516, Jun. 2007, doi: 10.1109/TASC.2007.899648.

[7] N. Cheggour et al., "Reversible axial-strain effect and extended strain limits in Y-Ba-Cu-O coatings on deformation-textured substrates," *Appl. Phys. Lett.*, vol. 83, pp. 4223–4225, 2003, doi: 10.1063/1.1628818.

[8] K. Ilin et al., "Experiments and FE modeling of stress-strain state in ReBCO tape under tensile, torsional and transverse load," *Supercond. Sci. Technol.*, vol. 28, 2015, Art. no. 55006, doi: 10.1088/0953-2048/28/5/055006.

[9] H. S. Shin, J. R. C. Dizon, T. H. Kim, D. W. Ha, and S. S. Oh, "Critical current degradation behavior in YBCO coated conductors under torsional strain," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 3274–3277, Jun. 2007, doi: 10.1109/TASC.2007.897458.

[10] N. C. Allen, L. Chiesa, and M. Takayasu, "Structural modeling of HTS tapes and cables," *Cryogenics (Guildf)*, vol. 80, pp. 405–418, 2016, doi: 10.1016/j.cryogenics.2016.02.002.

[11] J. Fleiter, M. Sitko, and A. Ballarino, "Analytical formulation of Ic dependence on torsion of YBCO and BSCCO conductors," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 3–6, Jun. 2013, doi: 10.1109/TASC.2012.2228292.

[12] H. S. Shin, J. R. C. Dizon, T. H. Kim, D. W. Ha, and S. S. Oh, "Critical current degradation behavior in YBCO coated conductors under torsional strain," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 3274–3277, Jun. 2007, doi: 10.1109/TASC.2007.897458.

[13] H. S. Shin, M. J. Dedicatoria, H. S. Kim, N. J. Lee, H. S. Ha, and S. S. Oh, "Electro-mechanical property investigation of striated REBCO coated conductor tapes in pure torsion mode," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2997–3000, Jun. 2011, doi: 10.1109/TASC.2010.2096450.

[14] A. Gorospe, Z. Bautista, and H. S. Shin, "Critical current degradation behaviour of GdBCO CC tapes in pure torsion and combined tension-torsion modes," *Supercond. Sci. Technol.*, vol. 29, no. 10, pp. 1–9, 2016, doi: 10.1088/0953-2048/29/10/104003.

[15] A. KB, R. J. Thomas, J. P. Mathai, and A. Nijhuis, "Analytical and numerical investigations on the degradation of REBCO based superconducting tapes under bending," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 7, Oct. 2021, Art. no. 8400712, doi: 10.1109/TASC.2021.3109720.

[16] K. B. Ashok et al., "Parametric investigation on the thermal aspects of superconducting REBCO tapes used in CORC cables," *Mater Today Proc.*, vol. 41, pp. 676–680, 2020, doi: 10.1016/j.matpr.2020.05.381.

[17] J. R. C. Dizon, A. R. N. Nisay, M. J. A. Dedicatoria, R. C. Munoz, H. -S. Shin, and S. -S. Oh, "Analysis of thermal residual stress/strain in REBCO coated conductor tapes," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art no. 8400905, doi: 10.1109/TASC.2013.2292746.

[18] K. B. Ashok, R. J. Thomas, M. J. Prakash, and A. Nijhuis, "Performance limits in REBCO tape for variation in winding parameters of CORC® cable and wire," *Phys. C Supercond. Appl.*, vol. 582, 2021, Art. no. 1353828, doi: 10.1016/j.physc.2021.1353828.

[19] H. Conrad, T. Klose, T. Sandner, D. Jung, H. Schenk, and H. Lakner, "Modeling the thermally induced curvature of multilayer coatings with COMSOL multiphysics," in *Proc. COMSOL Conf.*, 2008, pp. 1–5.

[20] M. Takayasu, J V. Minervini, and L. Bromberg, "Torsion strain effects on critical currents of HTS superconducting tapes," *AIP Conf. Proc.*, vol. 1219, pp. 337–344, 2010, doi: 10.1063/1.3402320.

[21] "2G Strain effect measured by Danko van der Laan," NIST, 2006. [Online]. Available: http://superpower-inc.com

[22] P. Gao, J. Mao, J. Chen, X. Wang, and Y. Zhou, "Electromechanical degradation of REBCO coated conductor tapes under combined tension and torsion loading," *Int. J. Mech. Sci.*, vol. 223, 2022, Art. no. 107314, doi: 10.1016/j.ijmecsci.2022.107314.

Ashok KB was born in Wayanad, India, in 1990. He received the bachelor's degree from Calicut University, Malappuram, India, in 2013 and the master's degree (with specialization in industrial refrigeration and cryogenics engineering) from University of Kerala, Thiruvananthapuram, India, in 2016, both in mechanical engineering. He is currently working toward the Doctorate degree in superconductivity from APJ Abdul Kalam Technological University, Thiruvananthapuram, India.

He was a Research Assistant with the EMS group University of Twente, The Netherlands for eight months in 2016. From 2017 to 2018, he was an Assistant Professor with the Department of Mechanical Engineering, Engineering College in Kottayam, APJ Abdul Kalam Technological University, Kerala, India. He has authored and coauthored and presented five research papers till now. His research interests include superconductivity, cryogenics, heat transfer, fluid flow, and solid mechanics.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.

Rijo Jacob Thomas received the Graduate degree in mechanical engineering from Periyar University, Salem, India in 2002, the Postgraduate degree in mechanical engineering with specialization in industrial refrigeration and cryogenics engineering from TKM College of Engineering, Kerala University, Thiruvananthapuram, India in 2006, and the Ph.D. degree in cryogenics from the Indian Institute of Technology Kharagpur (IIT Kharagpur), Kharagpur, India, in 2011.

He is currently an Assistant Professor with the Department of Mechanical Engineering, TKM College of Engineering, Kollam, India. He has authored and coauthored more than 50 research papers in journals/conferences. He has carried out collaborative research work with Karlsruhe Institute of Technology, Germany, University of Twente, The Netherlands, IIT Kharagpur, and IISc, Bangalore, Institute of Plasma Research, Gujarat, India. He was the investigator for three funded research projects under BRNS, Department of Atomic Energy, Government of India. His current research interests include cryogenic and refrigeration systems, superconductivity, and process modeling.

Dr. Thomas is a reviewer for many reputed international journals in the field including *Elsevier-Energy*, *Applied Thermal Engineering, Cryogenics*, *International Journal of Refrigeration*, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, and so on.

Jose Prakash Mathai received the B.Tech. degree from TKM College of Engineering, Kerala University, Thiruvananthapuram, India, in 1985, the M.Tech. degree (specialization in propulsion engineering) from the College of Engineering, Trivandrum, India, in 1991, and the Ph.D. degree from the Indian Institute of Science, Bangalore, India, in 2000, both in mechanical engineering.

He was a Professor with TKM College of Engineering, Kollam, India and he is currently the Principal of TKM Institute of Technology, Kollam, India. He has carried out seven sponsored projects. He has authored and coauthored more than 50 papers in international journals/conferences. His research interests include thermal management of electronic systems, nanofluids, rocket combustion, and superconductivity.

Dr. Mathai is a Reviewer of more than ten reputed international journals.

Arend Nijhuis was born in Wierden, The Netherlands, in 1958. He received the B.S. and M.S. degrees in applied physics from Saxion University, Enschede, The Netherlands, in 1981, and the Ph.D. degree in applied physics from the University of Twente, Enschede, The Netherlands, in 2017.

From 1982 to 1985, he was a Researcher with the OCE R&D Department. Since 1985, he has been with the Faculty of Applied Physics, University of Twente, Enschede, The Netherlands. He has authored more than 200 articles and supervised many Ph.D. students. His research interests include high current, low and high-temperature superconductors and their applications with a particular focus on experiments and modeling on superconducting cables.

Authorized licensed use limited to: UNIVERSITY OF TWENTE.. Downloaded on December 20,2023 at 13:56:18 UTC from IEEE Xplore. Restrictions apply.